THE ACETYLENE-ELECTRIC FLAME

OR

PHYSICAL PROPERTIES OF FLAMES WHEN CARRYING ELECTRIC CURRENTS

By

C. F. LORENZ

DISSERTATION

SUBMITTED TO THE BOARD OF UNIVERSITY STUDIES OF THE JOHNS HOPKINS UNIVERSITY IN CONFORMITY WITH THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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OUTLINE

INTRODUCTION

Survey of work done on the electrical behavior of flames.

Scope of the present investigation.

EXPERIMENTS WITH SMALL CURRENTS

Deflection of a flame toward a cathode, including a description of the phenomenon and a theory of its explanation.

EXPERIMENTS WITH LARGER CURRENTS

Shortening of a flame under heavy discharge.

Increase of luminosity.

Choice of gas for utilization of increase of luminosity.

Deposit of Soot

Electrical and Photometric Measurements

Relation between Candle-Power and Current and between Current and Voltage

Comparison of Operation at different Gas-Pressures in regard to highest Candle-Power attainable

Comparison of Candle-Power attainable with Direct Current and Alternating Current

Effect of Material of Electrodes

Photographs on a Moving Plate

Color of the Flame

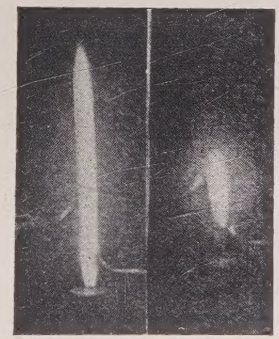
The Current-Carrying Acetylene Flame as an Illuminant

Its use in Photography and Spectroscopy

The Acetylene-Electric Flame

By C. F. Lorenz

That flames exhibit certain peculiarities under electrical influences has been known since the earliest days of electrical science, and their behavior in this respect has been the subject of a very large number of investigations. These cover the following classes of phenomena: the conduction of currents of electricity by flames, the yielding of currents by a flame when wires leading to a galvanometer are unsymmetrically placed in it; the distortions that a flame may be made to undergo when brought into various relations with charged bodies. The more modern work has been confined to the first of these subjects, and in particular to the conduction of currents that are very small, usually of the order of several micro-amperes, both in flames modified in their conducting properties by the addition of various salts and in so-called "pure flames," that is, flames not containing salt vapors. The experiments described in the present article relate to the more old-fashioned topic of electrically caused flame distortions, together with an associated phenomenon, namely, an increase of luminosity that may be obtained by sending current through carbon-containing flames. Attention has already been called to the latter effect by the writer,[1] the first experiments having been performed with alternating current, with which the requisite high voltage is readily obtained by means of a transformer. Opportunity has since occurred of extending these experiments in the physical laboratory of the Johns Hopkins University, where a source of direct current at 4000 volts or 5000 volts became available.



FIGS. 1 AND 2—SHORTENING OF FLAME DUE TO HEAVY CURRENT

This source consisted of a set of five small generators having their armatures in series. Besides facilitating the electrical measurements, direct current has the important advantage that its use avoids the confusion of the effects at the two electrodes which necessarily occurs with alternating current.

[1] *Phys. Zeit.*, Vol. 8, page 20; 1907.

Deflection of a Flame Toward a Cathode

The results obtained by the early investigators who examined the distortions which a flame undergoes in an electric field are somewhat complicated. The most prominent phenomenon observed was an apparent attraction of at least part of the flame by a negatively charged body. Various hypotheses have been proposed to account for this—for example, one of the possibilities suggested by J. J. Thomson[2] is that perhaps "corpuscles" are given off by the molecules of the hot gases, leaving the latter positively charged. The following experiment suggests an explanation entirely different from this and from any that has heretofore been advanced.

Description of the Phenomenon

The flame used was a simple cylindrical jet burning from a pin-hole burner. The gas used was acetylene, though this particular phenomenon can be observed just as well with coal gas or hydrogen. An important part of a simple cylindrical flame is the invisible mantle of vapor which envelops the visible part and extends far up above it, and which shows when a shadow of the flame is thrown upon a screen by means of a beam of sunlight or arc light. Such a shadow picture was formed, and by watching the latter the electrodes could have given them any desired position with respect to the mantle. Instead of using a static machine to charge the conductors brought near the flame, as has been done in the past, use was made of the generators; a high resistance was put in series to prevent a short-circuit in case the terminals were brought too close together.

When the machines are run at 2000 volts or 3000 volts and the negative terminal is brought near the flame—say at a height half-way between the base and the tip—no deflection whatever of the flame is observed, provided everything is well insulated, and this is so even if the negative terminal is brought well within the flame's mantle of hot vapor. On bringing the positive terminal of the machines up on the opposite side, but not touching the invisible mantle, a very slight deflection of the flame toward the cathode is observed. The moment the positive terminal is brought close enough to touch the mantle as observed in the shadow picture the flame is strongly deflected toward the cathode and may even come in contact with it. A galvanometer inserted in the circuit, showing no current so long as the positive terminal is outside the mantle, suddenly indicates a current as soon as the mantle is touched by the electrode. The deflection occurs no matter what part of the mantle is

[2] "Conduction of Electricity Through Gases," Chapter IX.

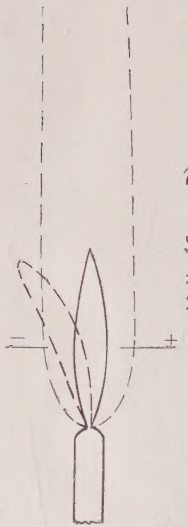


FIG. 3—DEFLECTION OF FLAME TOWARD A CATHODE

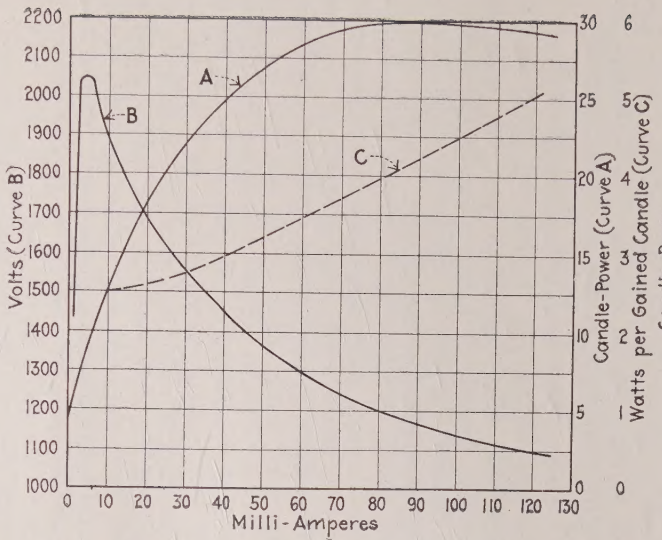


FIG. 4—CANDLE-POWER-CURRENT, CURRENT-VOLTAGE AND CURRENT-WATTS-PER-GAINED-CANDLE-POWER RELATIONS

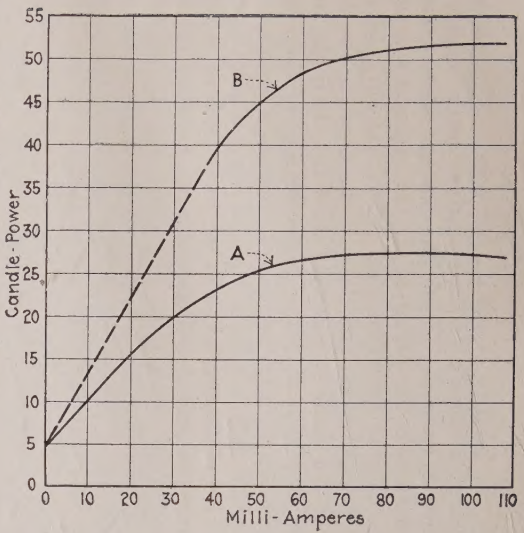


FIG. 5—CANDLE-POWER-CURRENT RELATIONS AT DIFFERENT GAS PRESSURES

touched by the positive terminal, and occurs even if the latter is placed alongside of the negative terminal only a few millimeters from it. If the phenomenon were purely an electrostatic one, the effects of the two electrodes would in this case have to neutralize each other. As the positive terminal is brought closer and closer to the negative one the deflection of the flame is increased until the electrode distance is so short that a visible discharge forms, when the flame resumes its normal position. As soon as a visible discharge appears only a minute spot on the cathode forms the base of the discharge, while in the conduction of a very small current the whole cathode surface immersed in the mantle presumably takes part. By observing the shadow picture it is seen that the deflection of the flame proper is accompanied by a movement of the mantle in the same sense, and also that the flame gases seem to move along the negative wire away from the tip. The deflection effect can be imitated perfectly by sucking through a glass tube the open end of which replaces the cathode. It is surprising how strongly the air must be drawn through the tube to give the same result as that produced electrically.

Explanation of the Deflection

From the observations just described it seems evident that the deflection effect depends in some way upon the flow of current, instead of being a purely electrostatic interaction between a negatively charged body and charges produced by combustion or temperature. In the light of what is now known in regard to the nature of conduction of electricity through gases the explanation seems clear. We have only to remember the high resistance at a cathode owing to the scarcity of ions at the surface of the latter, this scarcity itself being caused by the fact that the solid electrode does not furnish carriers to replace those swept out of the region adjacent to the cathode in the act of conduction. For minute currents there is a fall of potential at the cathode which is proportional to the current, and which is of the same nature as that which occurs at those electrodes of a mercury-arc rectifier which are anodes for the passed half-waves but cathodes for the reverse half-waves. There is, similarly, a scarcity of positive carriers at the surface of the anode in the flame, but the "cathode drop" is much greater than the "anode drop" because of the greater mobility of the negative carriers. On account of this high cathode resistance the flame is prevented from acquiring the potential of the cathode, but it does take on approximately the potential of the positive electrode. Consequently attraction occurs between the cathode and the flame-gas near it, causing motion of the latter along the

cathode and a consequent local diminution of pneumatic pressure which results in a deflection of flame and mantle. The fact that for minute currents the drop at the cathode is proportional to the current agrees with the observation that the deflection increases as the anode is brought closer and closer to the cathode. The observed ceasing of the deflection as soon as a visible discharge appears at a spot on the cathode is to be expected since the copious supply of ions at the locally heated spot would end the existence of the high cathode resistance.

Shortening of a Flame Under Heavy Discharge

Another very striking distortion of a simple cylindrical flame is a shortening which occurs when it is traversed by currents larger than those which give the deflection toward the cathode. As soon as the current is made great enough to give a visible discharge a shortening is observable; as the current is increased the flame continues to shorten down to say one-half or one-third its original length. The effect is shown by the halftones Figs. 1 and 2, the former being an uninfluenced acetylene flame and the latter the same flame when traversed by a current of 1/10 amp. This shortening is doubtless to be ascribed to the increased rate at which combustion takes place when the temperature of the flame is raised by the discharge—the size of a flame being always determined by the condition that its surface must be just great enough for the rate of combustion of the gas to equal the rate of supply.

Increase of Luminosity

The light emitted by a flame, luminous owing to the presence of free carbon, can be increased both in quantity and whiteness by the passage through the flame of an arc-like discharge such as that given by an induction coil when the primary is supplied with alternating current. If the flame is one that has but little "stiffness," such as any flame burning from a wick or a gas flame operating at low pressure, then the flame will be so much distorted by the discharge that it would be hopeless to try to make any measurements. On the other hand, if a cylindrical gas jet issues at considerable pressure from a burner of fine bore it will burn quite steadily even while the discharge is passing through it, provided there be a suitable disposition of the electrodes, as described below.

Choice of Gas

When illuminating gas is used the increase of luminosity owing to the discharge, though easily perceptible, is not very striking, but in the case of a gas containing a greater

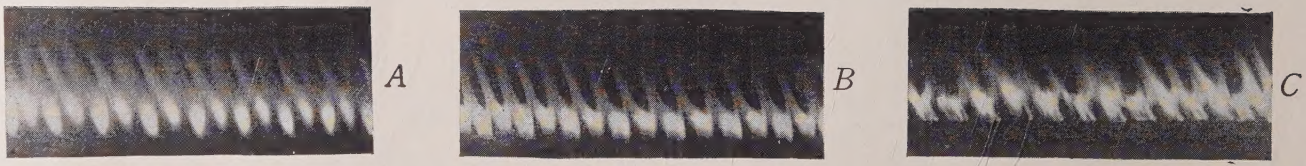


FIG. 6—PHOTOGRAPHIC REPRODUCTIONS OF FLAME SUPPLIED WITH ALTERNATING CURRENT

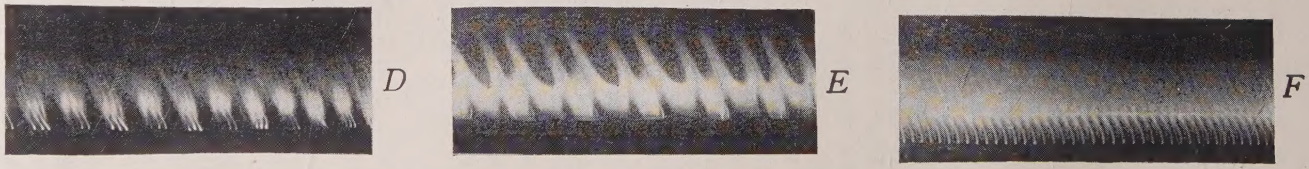


FIG. 7—PHOTOGRAPHIC REPRODUCTIONS OF FLAME WHEN SHUNTED BY INDUCTANCE AND CAPACITY

FIG. 8—PHOTOGRAPHIC REPRODUCTIONS OF FLAME UNDER ACTION OF DIRECT CURRENT

percentage of carbon the increase may amount to several times the original value. The most suitable gas is acetylene, C_2H_2, on account of its high carbon content together with its high temperature, the latter making it capable of being burned in a sufficiently "stiff" flame. The vapor of benzene, C_6H_6, has the same percentage of carbon, and its use would be very convenient, but it cannot be burned under sufficient pressure. The velocity of the issuing jet, if great enough to give the required stiffness, is greater than the velocity with which the ignition is propagated toward the burner, this velocity being rather small on account of the comparatively low temperature of the benzene flame. The same is true of the vapors of other carbon compounds which are liquid at ordinary temperatures and capable of being readily vaporized, such as amyl-acetate, pentane, xylene, etc. These were vaporized in a small closed brass vessel into which the thimble-like burner tube was directly soldered, the vessel being electrically heated so that the flame could be readily controlled by a rheostat. To use such fuels at all for the purpose in question it is necessary to start the discharge with the flame burning low; on then increasing the pressure, the flame, though no longer reaching down to the burner, continues to burn between and above the electrodes, where the temperature is raised by the discharge. To the benzene flame there is also the objection that it is very smoky. With acetylene none of these troubles exist. All the measurements of candle-power given below refer to this gas.

Deposit of Soot

In order to have a flame that contains suspended carbon burn satisfactorily while carrying a current it is necessary to avoid the deposit of soot upon the electrodes. If an electrode touches the luminous part of the flame a surprisingly large amount of soot will build itself upon it, sometimes forming a tree-like growth that may reach from one electrode to the other. For this reason the burner cannot be used for one electrode, as the soot would interfere with the flow of gas. Heating the electrodes is ineffectual in preventing this deposit of soot. The deposit is, doubtless, due to electrostatic attraction. This would account for the tree-like character of the deposit, as the electric force would always be strongest at the tips of the branches. The trouble from the soot may be entirely avoided by keeping the electrodes out of the luminous part of the flame, having it only in the invisible mantle of hot gases surrounding the flame. The best arrangement is to have one electrode near the base of the flame and the other on the other side about one-third or one-half way up to the tip. In spite of this unsym-

metrical arrangement the flame does not lose its appearance of symmetry. There is not merely an arc through the flame from one electrode to the other, but the whole flame seems to take part in the discharge. If the current is very strong the arc can be traced; it is blown by the flame past the upper electrode and curves down to meet the electrode. The steadiness obtainable depends very much on the proper shape and adjustment of the electrodes as the base of the discharge has a tendency to shift about on the electrode. It is best to give the electrodes, consisting of bluntly pointed wires, an upward slant at the end.

Electrical and Photometric Measurements

It seemed worth while to obtain some quantitative data in regard to the conduction of current by the flame and in regard to the candle-power changes, and to this end apparatus was arranged so that sets of simultaneous readings of current, difference of potential between electrodes, and candle-power could be made. The current through the flame was read on a Weston instrument and difference of potential between flame electrodes on a Kelvin electrostatic voltmeter. In series with the flame it was, of course, necessary to have a certain amount of resistance to preserve the equilibrium. For the photometric measurements a simple flicker photometer was used, because the variation in whiteness of the flame with variation of current made it impossible to make reliable settings with a Lummer-Brodhun or Bunsen photometer. In all cases given the horizontal candle-power of the flame was measured in terms of the candle-power of a standardized incandescent lamp.

Relation Between Candle-Power and Current and Between Current and Voltage

The curves in Fig. 4 show the result of a set of such readings. In this run the voltage at the generators' terminals was left unchanged at 3300 volts, the current being varied by means of the series resistance. The flame height was 40 mm, the gas-pressure at the burners 67 mm of water, and the rate of flow of gas was given by a rate-meter as 0.23 cu. ft. per hour. The vertical distance between the electrodes, which were made of copper, was 11 mm.

It will be observed that there is a gradual increase of candle-power with current up to a limiting value, which in the present example is approximately five times that of the uninfluenced flame. With very large currents there is a slight falling off of candle-power. The points near the beginning of the two curves show that the increase of

candle-power begins while the discharge is still in the "glimm-strom" stage, before a true arc is formed. The dotted line shows the variation of the "specific consumption" in watts per candle as the current is varied, the lowest value on the curve corresponding to 2.5 watts per gained candle. This may be materially reduced by operating the flame at a lower gas-pressure, for the reason given in the next paragraph.

Comparison of Operation at Different Gas Pressures in Regard to Highest Candle-Powers Attainable

It seemed probable that with burners of different bore, operated respectively at such pressures that the rate of flow of gas was the same for all, the candle-power attainable would be the same for all, but the following experiment shows that this is by no means the case. Candle-powers and currents were measured for two burners in succession, leaving the electrodes undisturbed but changing the burners. With the aid of a simple gas-flow indicator of the kind described by Tufts,[3] the rate of flow for the two burners was made the same, this being about 0.25 cu. ft. per hour. The results are shown in the curves given in Fig. 5. It is seen that, though for the flame without the discharge the candle-power is approximately the same for both pressures, the candle-power attained with current is greater the less the pressure needed to give the same rate of flow. Therefore it is advantageous, when using a current-carrying acetylene flame as a source of light, to choose a jet that will give a flame only just stiff enough not to be distorted by the discharge. The explanation may lie in the fact that the greater the velocity of the jet the more air is dragged along by the flame, and consequently the more rapid the combustion and thus the less the amount of free carbon present.

Comparison of Candle-Power Attainable with Direct Current and Alternating Current

From the fact that with alternating current the discharge is practically zero during a considerable fraction of the period (since the difference of potential at the terminals has to rise to a certain value before the discharge begins), combined with the fact that the highest candle-power attainable is limited no matter how heavy the discharge, one would expect that the value to which the candle-power could be pushed would be higher with direct current than with alternating current. This is shown to be the case by the following comparison; the direct and alternating currents

[3] F. L. Tufts, *Phys. Rev.*, Vol. XXII, page 193; 1906.

were each made great enough to give the limiting value of the candle-power: Flame without current, 5.3 cp; flame with alternating current, 28.8 cp; flame with direct current, 44.2 cp.

Effect of Material of Electrodes

Using direct current, it is only the cathode that is heated to any extent by a current sufficient to give the limiting value of the candle-power. A platinum cathode will become white hot and melt; if coated with calcium-oxide it will remain comparatively cool (only red hot) until the oxide is all volatilized, which soon occurs if it is only a thin coating. A piece of metallic calcium serves very well as a cathode, the base of the discharge then being a minute spot on the oxidized surface. To determine the effect of the material of the cathode upon the candle-power attainable a direct comparison was made of the following: copper, iron, titanium, magnesium, manganese, cadmium, silver, platinum, calcium and carbon. It was found that except for slight discrepancies caused by the position of the cathode, the same photometer reading gave a balance for all, the current being made great enough to give the limiting value of the candle-power.

Photographs on a Moving Plate

The increase of luminosity caused by the discharge is shown by photographs taken on a moving plate when the flame is operated on alternating or intermittent current. In Fig. 6, page 501, *A* and *B* show the result of supplying the flame with ordinary 60-cycle alternating current, the current strengths being 3 and 10 centi-amperes respectively. The discharge begins and ceases each time the potential difference rises and falls to certain critical values, and in that part of the period during which the potential difference lies below this value the flame regains nearly its original height. In *C* is shown the effect of shunting the flame (supplied with alternating current) with a condenser; the discharge is then irregular and emits a crackling sound, the same as with a much higher difference of potential in air. If the flame is shunted by inductance and capacity in series, the discharge is much more regular, as is shown by *D* and *E* in Fig. 7.

The remaining photographs show the results obtained with direct-current supply. In *F* the capacity was large compared with the inductance and the note emitted not agreeable. Increasing the inductance gives the effects in Fig. 8 (*G* and *H*), and *I* was taken while the cathode (upper electrode) was of calcium. In the last three cases the note emitted was of considerable purity. By suitable

adjustment of induction and capacity it was easy to vary the frequency of discharge from values too low to give an audible note up to values that were too high.

Color of the Flame

The high temperature to which the carbon is raised by the discharge makes the light emitted much whiter than that of a flame without discharge, as can be most readily shown by allowing the two sources to cast adjacent shadows of a pencil on a white screen. The shadow receiving light only from the current-carrying flame appears blue compared with the other. On the other hand, the light is yellower than that from the crater of a carbon arc.

The Current-Carrying Acetylene Flame as an Illuminant

This combination of acetylene flame with small-current, high-potential arc is worth some attention as an illuminant, though the high voltage required and the rather high specific consumption detract from its interest in this respect. The "radiant efficiency" is large, owing to the high temperature of the carbon particles, but the specific consumption is high on account of a high conduction-convection loss. The combination may from one standpoint be looked upon as a carbon-incandescent lamp having the filament material continually renewed, and from another as a small-unit flaming arc in which the electrodes are not consumed and the luminous material is the carbon supplied by the acetylene.

Its Use in Photography and Spectroscopy

Owing to the high temperature attained by the carbon particles the current-carrying acetylene flame compares with other continuous-spectrum illuminants (with the exception of the arc) much more favorably in photographic efficiency than in candles-per-watt output. It may also be useful in spectroscopic work as a source of radiation when strength in the violet and ultra-violet of a continuous spectrum is needed. Although its intrinsic brilliancy is less than that of the crater of a carbon arc, it has the advantage that it presents a larger radiating area than the hottest part of the arc, which is only a spot, and also of running indefinitely without attention. Spectral reference lines can be conveniently obtained by shunting the flame with a condenser during a part of the exposure when lines corresponding to the material of the electrode are superposed on the continuous spectrum.

The writer takes pleasure in acknowledging the helpful suggestions received from Prof. J. S. Ames during the course of these experiments.

BIOGRAPHICAL SKETCH.

Charles Frederick Lorenz was born March 1, 1875 in Burlington, Iowa. He received his early education in the public schools of that city and after two years spent in the employ of the Burlington Electric Lighting Co., entered the State University of Iowa in 1894. He received the degree of B. S. in 1897 and M. S. in 1898, having been Fellow in Physics for the year 1897-1898. The subsequent time was spent as follows: Draughtsman with Morgan-Gardener Electric Co., Chicago, 1898-1899; Student in Physics in the University of Chicago 1899-1900; Instructor in Physics in the University of Iowa 1900-1906; Student in the Johns Hopkins University since October 1906. He has attended courses given by Professors Ames, Wood, and Whitehead (in Physics), Jones (in Physical Chemistry), and Cohen (in Mathematics).